New Physics and Recent High Precision Electroweak Measurements

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Abstract

We analyze LEP and SLC data from the 1995 Winter Conferences for signals of new physics. We compare the data with the Standard Model (SM) as well as a number of test hypotheses concerning the nature of new physics: (i) nonstandard $Zb\overline{b}$ couplings, (ii) nonstandard $Zf\overline{f}$ couplings for the entire third generation, (iii) nonstandard oblique corrections, (iv) nonstandard lepton couplings, (v) general nonstandard W and Z couplings to all fermions, as well as combinations of the above. In most of our analyses, we leave the SM variables α_s and m_t as free parameters to see how the various types of new physics can affect their inferred values. We find that the best fit ($\chi^2/$d.o.f. $= 8.4/10$) is obtained for the nonstandard $Zb\overline{b}$ couplings, which also give a 'low' value (0.112) for α_s. The SM also gives a good description of the Z data, having $\chi^2/$d.o.f. $= 12.4/12$. If α_s is held fixed to the low-energy value 0.112, then we find that a combination of the nonstandard $Zb\overline{b}$ couplings is fit to lie more than four standard deviations away from zero.

1. Introduction

Recently announced results from LEP (Moriond 1995) boast an overall energy error of 1.5 MeV in the measurement of the Z-mass (*i.e.* one part in 10^5), and an error of roughly one part in 10^3 for Z-decay rates and branching ratios. In fact, the LEP experiments are even sensitive to such small gravitational effects as the tidal forces due to the sun and the moon, as well as due to changing water levels in Lake Geneva. Moreover, the experimental error for the SLC measurement of the asymmetry A_{LR} is a remarkable 0.4%. Such high precision permits very rigorous tests of the standard model (SM) of the strong and electroweak interactions. With this precise data, one hopes to find discrepancies between experiment and SM predictions, and to thereby gain an indication of the kind of the new physics which will ultimately prevail in its stead.

This letter reports on our most recent analysis of Z-pole data for indications of new physics. This analysis differs from those that have been done previously in two important ways: (*i*) it includes the most recent results reported by the experimental groups in the 1995 winter conferences, and (*ii*) it tests a large number of hypotheses of new physics, and is not limited to a consideration of the specific forms which have often been used in the past (such as 'oblique' [1], [2], [3], [4], [5] and/or new $Zb\bar{b}$ couplings [4], [6]). We are able to perform a broader survey of the theoretical possibilities by taking advantage of the effective-lagrangian approach recently proposed in ref. [7]. This approach entails only a bare minimum of theoretical prejudice, our goal being to give the data as free a hand as possible to indicate in which direction new physics lies.

We organize the presentation of our results as follows. We first briefly review the general effective lagrangian used to parametrize new physics effects at the Z pole. This is followed by a summary of the most recent experimental data. We then compare the data with several test hypotheses concerning the nature of the new physics, considering a wide variety of choices of combinations of effective couplings. This comparison permits a quantitative statistical evaluation of the relative compatibility of each hypothesis with the data. Our conclusions are finally summarized in the last section.

2. Parameterizing the New Physics

Based on the effective-lagrangian approach outlined in [7], the present analyses incorporates all of the potential effective operators which can arise up to and including dimension four. This involves three different kinds of nonstandard interactions. The first kind consists of nonstandard contributions to electroweak boson propagation, as can be

parameterized using the usual oblique parameters S and T. Next, there are non-standard neutral-current $Zf\overline{f}$ interactions, which we normalize according to

$$\mathcal{L}_{\text{eff}}^{\text{nc}} = -\frac{e}{s_w c_w}\overline{\psi}_f \gamma^\mu \left[\left(g_L^f + \delta g_L^f\right)\gamma_L + \left(g_R^f + \delta g_R^f\right)\gamma_R\right]\psi_f, \tag{1}$$

where the SM couplings are given in terms of the fermion's weak isospin and electric charge by $g_L^f = I_3^f - Q^f s_w^2$ and $g_R^f = -Q^f s_w^2$. $s_w = \sin\theta_W$ where θ_W is the usual weak mixing angle. Finally come nonstandard fermion-W couplings, whose strength we parameterize by $\delta h_L^{ff'}$ and $\delta h_R^{ff'}$, where the normalization is such that the SM contribution for leptons is $h_L^{ff'} = \delta_{ff'}$. It is an easy matter to derive predictions for observables in terms of these parameters [7], and these are most usefully cast as a SM prediction supplemented by a new-physics correction which is linearized in the new couplings S, T, g_L^f, etc..

All three classes of nonstandard interactions can contribute to precision measurements taken purely at the Z pole, although the nonstandard fermion-W interactions only appear through the specific combination $\Delta = \sum_{f=e,\mu}\left[\sqrt{\sum_i \left|\delta_{if} + \delta h_L^{\nu_i f}\right|^2} - 1\right] \approx \text{Re}\left(\delta h_L^{\nu_e e}\right) + \text{Re}\left(\delta h_L^{\nu_\mu \mu}\right)$. Only this combination appears because nonstandard fermion-W couplings play a role solely through their contribution to muon decay, from which the measured value of the Fermi coupling, G_F, is inferred. This value is relevant since G_F (together, of course, with α and M_Z), are used as inputs to define the SM predictions for the Z-pole observables.

At the outset, it therefore appears that new physics can affect the Z-pole observables through 19 new-physics parameters: $\{\delta g_{L,R}^f, S, T, \Delta\}$, with $f = e, \mu, \tau, u, d, s, c, b$. It is not possible, however, to simultaneously constrain all these parameters from Z-pole data since they do not all appear independently in the measured quantities. For example, Z-pole observables only depend on the quantities T and Δ through the combination $\alpha T - \Delta$ [7]. Because of this we ignore Δ in our fits, although all of our results for T are properly interpreted as constraints for $\alpha T - \Delta$. Similarly, since the hadron-related observables (which we take to be $A_{FB}(b)$, $A_{FB}(c)$, Γ_Z, $R_l \equiv \Gamma_{\text{had}}/\Gamma_l$ (for $l = e, \mu, \tau$), $\sigma_h \equiv 12\pi\Gamma_{\text{had}}\Gamma_e/M_Z^2\Gamma_Z^2$) only depend on the light-quark couplings through the hadronic width, Γ_{had}, the only measurable combination of these couplings is

$$\delta_{UD} \equiv \sum_{q=u,d,s}\left(g_L^q \delta g_L^q + g_R^q \delta g_R^q\right). \tag{2}$$

It must also be noted that neither of the oblique parameters, S and T, can be separated from the nonstandard $Zf\overline{f}$ couplings, if such new couplings are permitted for all species

of fermions. Additional information becomes available once other experimental quantities, such as M_W or low-energy scattering cross sections, are also considered. None of the fits reported here avail themselves of this additional information, however.

In analyzing the data we test a variety of assumptions concerning the nature of new physics, by imposing *a priori* relations amongst the nonstandard couplings. We imagine a series of cases ranging from the SM only to a fit in which as many constrainable parameters as possible are allowed to float. Intermediate cases include permitting only nonstandard $Z b \overline{b}$ couplings, $\delta g^b_{L,R}$; permitting nonstandard $Z f \overline{f}$ couplings for the entire third generation, $\delta g^b_{L,R}, \delta g^\tau_{L,R}$; permitting only oblique corrections, S and T; permitting light-lepton couplings, $g^e_{L,R}, g^\mu_{L,R}$; as well as various combinations of these alternatives.

3. Data Analysis and Discussion

The 1995 winter conferences saw the release [8] of new numbers from the LEP experiments for observables on the Z pole. The numbers for those observables which we use in our analysis, together with the most recent figure from SLC [9] for A_{LR}, are listed in Table I. Although we do not list them explicitly here, we take the experimental correlations for the LEP observables from ref. [8].

We have fit these observables using a variety of assumptions concerning the nature of new physics. We give a representative set of the results which come from these fits in Table II through VIII. For Tables III through VIII, which describe the results of fits which include the influence of new physics, the column labelled 'Pull' indicates the deviation from zero of the best-fit value for each new-physics parameter, in units of the standard deviation for that parameter. This quantifies the extent with which the data prefer these nonstandard couplings to be nonzero.

A few other points of explanation concerning these tables are in order.

● *(1) The SM Fit:* Table II lists the values for the strong coupling constant, $\alpha_s(M_Z)$, and the top-quark mass, m_t, that are obtained by fitting the data of Table I to the SM predictions. We choose the fiducial value $m_H = 300$ GeV for the Higgs mass in all of our fits, and ignore the comparatively weak dependence of the observables on m_H. This fit is meant to verify that our fits reproduce the usual results for $\alpha_s(M_Z)$ and m_t when they are restricted to the SM case, as well as to establish a baseline against which to compare the quality of the fits to extensions of the SM.

● *(2) Sensitivity to m_t:* We find that, irrespective of the types of new physics which are assumed, fits in which m_t floats generally give values of m_t that are clustered around the

value obtained from our SM fit (174± 8 GeV for fits based on LEP data only, 180± 7 GeV for fits based on LEP data and SLC). Thus, leaving m_t free to float in fits including new physics does not appreciably improve agreement with the data. Moreover, we see that the new physics we consider does not ruin the agreement between the value for m_t that is inferred from Z physics, and that which has been found from the kinematics of t production at Fermilab [10].

Since the dominant m_t dependence (*i.e.* those one-loop corrections proportional to $G_F m_t^2$) can be considered to be contributions to T and δg_L^b, one combination of m_t, T and δg_L^b becomes poorly constrained when all three of these parameters are free to float in a fit. In practice the same is approximately true if it is only T and m_t that float since most observables depend only weakly on δg_L^b. We therefore fix m_t in those fits which involve the oblique parameters, choosing $m_t = 179$ GeV, although we find our results do not depend strongly on the value chosen for m_t (within a few decades of 175 GeV).

• *(3) Inclusion of A_{LR}:* We have performed these fits with and without the SLC result for A_{LR}. As can be seen from the tables, the inclusion of A_{LR} always deteriorates the quality of the fit. This is because A_{LR} and the LEP observables independently measure, and give differing values for, the same combination (A_e) of electron couplings. Although new physics of the type we consider can change the value of A_e from the SM prediction, it appears in A_{LR} and the LEP measurements of A_e in the same way, and so cannot reconcile the two sets of experimental results. We interpret this to indicate the likely existence of an as yet unidentified source of systematic error in one or the other of these experiments. Until the source of this error is found, we quote our results both with and without the inclusion of A_{LR}.

Although it degrades the quality of the fits, the inclusion of A_{LR} generally does not much affect the values of the parameters for which χ^2 is minimized. Neither does it affect the orientation of the error ellipsoid, and so its inclusion does not change the 'optimal' combination of parameters, P_i, which is required to diagonalize the covariance matrix (see point *(4)* below). Its strongest influence is on the oblique parameter S which is only driven further away from zero (see Tables III and VI) by about one standard deviation. The right-handed b coupling (Tables IV and V) also gets somewhat shifted in this way.

• *(4) 'Optimal' Parameters:* Each of Tables III through VIII is divided into two main parts. The first of these parts directly gives the central values and one-sigma errors for the new-physics parameters that can be inferred from the given uncertainties in the experimental data. If this information were the entire story, then our results would indicate that the data in all cases implies that these nonstandard couplings are consistent with zero (the

SM prediction).

This conclusion is misleading, however, because it ignores the correlations amongst the nonstandard couplings that are imposed by the data. These correlations can be most simply illustrated for the scenario described in Table III, for which the only nonstandard quantities are the neutral current couplings of the b quark, $\delta g^b_{L,R}$. In this case the correlations which the data imply for these two parameters can be displayed by plotting the n-standard deviation ellipses in the $\delta g^b_L - \delta g^b_R$ plane. Such a plot, for the data in Table IVB, is given in Fig. (1).

This figure displays the results of the fit to the $Z b \bar{b}$ couplings, $\delta g^b_{L,R}$. In this fit the SM parameters are fixed to the values $m_H = 300$ GeV, $m_t = 177$ GeV, and $\alpha_s(M_Z) = 0.112$, leaving only the two parameters δg^b_L and δg^b_R free to float. The errors quoted in Table IVB for these couplings correspond to the projection of the one-sigma ellipse in this figure onto each of the two axes. Even though these projections separately indicate agreement with zero at the 1.5-σ level, the plot shows that the central values obtained in the fit are bounded away from the origin (0,0) by more than 4 sigma. (If the left-right asymmetry A_{LR} from SLC is included this deviation grows to around 5 sigma, although the quality of the agreement of the central value of the fit with the data becomes worse. Using only the previous 1994 LEP data [11] lowers the deviation to 3.5 sigma.)

When more than two parameters are fit, a similar plot of the multidimensional error ellipsoid is obviously less useful. As a result, we display the same information in a different way in the second parts of Tables III through VII. Here we define uncorrelated linear combinations, P_i, of the new physics parameters. These combinations diagonalize the covariance matrix which defines the error ellipsoid. We regard these parameters as being 'optimal' in the sense that they most reliably indicate the extent to which the new-physics couplings are bounded away from the origin. The central values and standard deviations for these optimal variables are quoted in the second parts of Tables III – VII.

• *(5) The Preferred Scenario:* The scenario which gives the best fit to the data (*i.e.* which has the lowest value for $\chi^2_{\min}/$d.o.f.) is that of Tables IV, in which the only new parameters which are entertained are nonstandard $Z b \bar{b}$ couplings. Considering only LEP data, we find $\chi^2_{\min}/$d.o.f. to be in this case 8.4/10, as compared to 12.4/12 for the corresponding SM fit. Although this is not overwhelming evidence against the SM, it is nonetheless suggestive. Table IVB shows that if m_t is fixed and a 'low' value for $\alpha_s(M_Z)$ is assumed to be given by the low-energy data, then $\chi^2_{\min}/$d.o.f. improves to 8.4/12.

The low $\chi^2_{\min}/$d.o.f. value for the fit with nonstandard $Z b \bar{b}$ couplings is not simply an instance of more parameters giving a better fit. The introduction of different or additional

6

new couplings also does not improve the description of the data. The preference for nonstandard b couplings is driven by the discrepancy between the measured value for R_b and its SM prediction. The introduction of nonstandard $Zb\overline{b}$ couplings is therefore guaranteed to improve the fit, provided that their contribution to the total hadronic width can somehow be compensated. Our fits acheive this compensation by having $\alpha_s(M_z)$ take smaller values than are found in the pure SM fit.[1]

• *(6) Implications for* $\alpha_s(M_z)$: Our SM fit, as reported in Table II, gives for the QCD coupling the value $\alpha_s(M_z) = 0.127 \pm 0.004$. This agrees with previous analyses of the 1994 data [11]. We find a similar value when the new physics is assumed to be purely oblique (Table IV). When all nonstandard $Zf\overline{f}$ couplings are permitted, then $\alpha_s(M_z)$ becomes poorly determined. This is because one combination of $\alpha_s(M_z)$ and the various new physics couplings tends to drop out of expressions for the observables. We have therefore fixed $\alpha_s(M_z)$ to be 0.125 in the fit of Table VIII. It must be noticed that $\chi^2_{\min}$/d.o.f. is also quite high (7.0/3) for this fit, corresponding to a confidence level of only 7%. Such a high value comes about because, although the value of $\chi^2_{\min}$ does not change with the addition of the extra parameters, the number of degrees of freedom decreases. This indicates that the additional parameters do not improve the description of the data.

The most interesting case is when the new physics involves nonstandard couplings to the third generation, such as is reported in Tables IV, V and VI. In this case $\alpha_s(M_z)$ is only slightly more poorly constrained than in the SM fit, but has a central value which is significantly smaller. These tables give $\alpha_s(M_z) = 0.112 \pm 0.009$. This correlation between new b physics and lower values for $\alpha_s(M_z)$ has also been noticed in the 1994 data [12].

As has recently been emphasized [13], the correlation between nonstandard $Zb\overline{b}$ couplings and a low value for $\alpha_s(M_z)$ is all the more interesting given that such low values are also fairly consistently indicated by other determinations of $\alpha_s(M_z)$ that are performed away from the Z resonance. Furthermore, ref. [13] argues that the QCD scale that is implied by this lower value for $\alpha_s(M_z)$ ($\Lambda_{QCD} \approx 200$ MeV) is also required for the success of other methods, such as the operator product expansion and QCD sum rules.

Since heavy new physics, as is described by an effective-lagrangian such as ours, does not influence $\alpha_s(M_z)$ as it is determined at low energies, a reasonable point of view would be to take the value for $\alpha_s(M_z)$ from the low-energy data where the contamination from new physics is negligible. Then this value can be used as a baseline to search for new physics signals in the data at the Z resonance. Such an approach has the advantage of making it difficult for new physics to hide in the uncertainties in the determination of

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[1] We thank Bob Holdom for useful conversations on this point.

$\alpha_s(M_z)$. Table IVB gives the result of such a fit. It is tantalizing that one obtains in this way a deviation from the SM in the b-couplings of 4.4 standard deviations!

4. Summary

We conclude that high precision Z-pole physics continues to quantitatively constrain new physics. Furthermore, the theoretical tools now exist to include a very general class of new physics in the analysis of the data in a model-independent way. The main result from the 1995 Winter Conferences is that the SM continues to successfully describe Z-pole physics, with no compelling deviations from its predictions seen in the data. That is not to say that new physics is thereby excluded, however, since the hypothesis that nonstandard $Zb\overline{b}$ couplings exist provides a better fit to the data than does the SM. This is due to the continued discrepancy between the measured value of R_b and its SM prediction. The new b couplings that are preferred by the data also continue to bring the inferred values for $\alpha_s(M_z)$ in line with those that are obtained in lower-energy determinations. Given the hypothesis that nonstandard neutral-current b couplings exist, and taking $\alpha_s(M_z)$ to be fixed at a low value, the latest data bounds the new couplings away from zero at the 4.4 sigma level, reinforcing the trend also found at a lower level in last year's results.

Acknowledgements

5. References

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Quantity	Experimental Value	Standard Model Fit
M_z (GeV)	91.1887 ± 0.0022	input
Γ_z (GeV)	2.4971 ± 0.0033	2.4979
σ_p^h (nb)	41.492 ± 0.081	41.441
$R_e = \Gamma_{\text{had}}/\Gamma_e$	20.843 ± 0.060	20.783
$R_\mu = \Gamma_{\text{had}}/\Gamma_\mu$	20.805 ± 0.048	20.783
$R_\tau = \Gamma_{\text{had}}/\Gamma_\tau$	20.798 ± 0.066	20.783
$A_{FB}^0(e)$	0.0154 ± 0.0030	0.0157
$A_{FB}^0(\mu)$	0.0160 ± 0.0017	0.0157
$A_{FB}^0(\tau)$	0.0209 ± 0.0024	0.0157
$A_\tau(P_\tau)$	0.140 ± 0.008	0.145
$A_e(P_\tau)$	0.137 ± 0.009	0.145
R_b	0.2204 ± 0.0020	0.2157
R_c	0.1606 ± 0.0095	0.172
$A_{FB}^0(b)$	0.1015 ± 0.0036	0.1015
$A_{FB}^0(c)$	0.0760 ± 0.0089	0.0724
A_{LR}^0	0.1637 ± 0.0075	0.145

TABLE I

The experimental values for the precision Z-pole observables considered in the present analysis.

Parameter	LEP Only	LEP and SLC
$\alpha_s(M_Z)$	0.127 ± 0.004	0.126 ± 0.004
m_t(GeV)	174 ± 8	180 ± 7
$\chi^2_{\min}$/d.o.f.	12.4/12 (42% C.L.)	19.0/13 (12% C.L.)

TABLE II: Standard Model

The SM parameters ($\alpha_s(M_Z)$ and m_t in GeV) as determined by fitting to the observables of Table I.

Parameter	LEP Only	Pull	LEP and SLC	Pull
S	-0.08 ± 0.20	0.4	-0.20 ± 0.20	1.0
T	-0.10 ± 0.22	0.5	-0.13 ± 0.22	0.6
0.73 S - 0.68 T	0.005 ± 0.085	0.1	-0.068 ± 0.079	0.9
0.68 S + 0.73 T	-0.13 ± 0.29	0.5	-0.23 ± 0.28	0.8
$\alpha_s(M_Z)$	0.127 ± 0.005		0.127 ± 0.005	
$\chi^2_{\min}$/d.o.f.	12.6/11 (32% C.L.)		17.6/12 (13% C.L.)	

TABLE III: Oblique Parameters

The oblique parameters S and T and the SM parameter $\alpha_s(M_Z)$ as determined by fitting to the observables of Table I. m_t is taken to be fixed at 179 GeV.

Parameter	LEP Only	Pull	LEP and SLC	Pull
δg_L^b	-0.0048 ± 0.0043	1.1	-0.0037 ± 0.0043	0.9
δg_R^b	0.001 ± 0.022	0.0	0.010 ± 0.022	0.5
$0.987\delta g_L^b - 0.160\delta g_R^b$	-0.0049 ± 0.0024	2.0	-0.0052 ± 0.0024	2.2
$0.160\delta g_L^b + 0.987\delta g_R^b$	0.000 ± 0.023	0.0	0.009 ± 0.022	0.4
$\alpha_s(M_Z)$	0.112 ± 0.009		0.109 ± 0.009	
m_t	177 ± 9		184 ± 8	
$\chi^2_{\min}$/d.o.f.	8.4/10 (59% C.L.)		14.1/11 (22% C.L.)	

TABLE IVA: Nonstandard $Zb\overline{b}$ Couplings

The new physics parameters δg_L^b and δg_R^b and the SM parameters $\alpha_s(M_Z)$ and m_t as determined by fitting to the observables of Table I.

Parameter	LEP Only	Pull	LEP and SLC	Pull
δg_L^b	-0.0047 ± 0.0037	1.3	-0.0038 ± 0.0037	1.0
δg_R^b	0.00050 ± 0.019	0.0	0.0094 ± 0.019	0.5
$0.98\delta g_L^b - 0.18\delta g_R^b$	-0.0048 ± 0.0011	4.4	-0.0055 ± 0.0011	5.0
$0.18\delta g_L^b + 0.98\delta g_R^b$	-0.00036 ± 0.020	0.0	0.0086 ± 0.020	0.4
$\chi^2_{\min}$/d.o.f.	8.4/12 (76% C.L.)		14.2/13 (36% C.L.)	

TABLE IVB: Nonstandard $Zb\overline{b}$ Couplings

The new physics parameters δg_L^b and δg_R^b as determined by fitting to the observables of Table I. In this fit we imagine obtaining the SM parameters $\alpha_s(M_Z)$ and m_t from experiments away from the Z pole (lower energies for $\alpha_s(M_Z)$ and Fermilab for m_t), and so fix them to $\alpha_s(M_Z)$=0.112 and m_t=177.

Parameter	LEP Only	Pull	LEP and SLC	Pull
δg_L^b	-0.0049 ± 0.0044	1.1	-0.0036 ± 0.0043	0.8
δg_R^b	0.000 ± 0.23	0.0	0.011 ± 0.022	0.5
δg_L^τ	-0.0002 ± 0.0011	0.2	0.0002 ± 0.0011	0.2
δg_R^τ	-0.0003 ± 0.0012	0.2	0.0001 ± 0.0012	0.1
P1	-0.001 ± 0.023	0.0	0.010 ± 0.023	0.5
P2	-0.0048 ± 0.0024	2.0	-0.0053 ± 0.0024	2.2
P3	-0.0007 ± 0.0014	0.5	-0.0003 ± 0.0014	0.2
P4	-0.00003 ± 0.00061	0.0	0.00005 ± 0.00061	0.1
$\alpha_s(M_Z)$	0.112 ± 0.009		0.109 ± 0.009	
m_t	176 ± 10		185 ± 9	
$\chi^2_{\min}/\text{d.o.f.}$	8.3/8 (40% C.L.)		14.1/9 (12% C.L.)	

$P1 \equiv 0.157\ \delta g_L^b + 0.987\ \delta g_R^b + 0.012\ \delta g_L^\tau + 0.008\ \delta g_R^\tau,$
$P2 \equiv 0.985\ \delta g_L^b - 0.156\ \delta g_R^b - 0.059\ \delta g_L^\tau - 0.049\ \delta g_R^\tau,$
$P3 \equiv 0.073\ \delta g_L^b - 0.026\ \delta g_R^b + 0.677\ \delta g_L^\tau + 0.732\ \delta g_R^\tau,$
$P4 \equiv 0.009\ \delta g_L^b - 0.004\ \delta g_R^b + 0.734\ \delta g_L^\tau - 0.679\ \delta g_R^\tau.$

TABLE V: Nonstandard Third Generation Couplings

The parameters $\delta g_L^b, \delta g_R^b, \delta g_L^\tau$ and δg_R^τ and the SM parameters $\alpha_s(M_Z)$ and m_t as determined by fitting to the observables of Table I.

Parameter	LEP Only	Pull	LEP and SLC	Pull
δg_L^b	-0.0041 ± 0.0053	0.8	-0.0004 ± 0.0050	0.1
δg_R^b	0.005 ± 0.027	0.2	0.026 ± 0.025	1.0
δg_L^τ	-0.0001 ± 0.0012	0.1	0.0006 ± 0.0011	0.6
δg_R^τ	-0.0000 ± 0.0013	0.0	0.0008 ± 0.0013	0.6
S	-0.10 ± 0.26	0.4	-0.33 ± 0.24	1.4
T	-0.11 ± 0.23	0.5	-0.16 ± 0.23	0.7
P1	-0.0050 ± 0.0024	2.1	-0.0050 ± 0.0024	2.1
P2	-0.002 ± 0.020	0.1	0.002 ± 0.020	0.1
P3	0.00004 ± 0.00060	0.1	0.00004 ± 0.00060	0.1
P4	-0.0002±0.0014	0.1	-0.0002 ± 0.0014	0.1
P5	-0.14 ± 0.33	0.4	-0.35 ± 0.31	1.1
P6	-0.02 ± 0.12	0.2	0.12 ± 0.11	1.1
$\alpha_s(M_Z)$	0.112 ± 0.009		0.110 ± 0.009	
$\chi^2_{\min}$/d.o.f.	8.2/7 (32% C.L.)		12.2/8 (14% C.L.)	

$P1 \equiv 0.985\ \delta g_L^b - 0.172\ \delta g_R^b + 0.00045\ S - 0.00034\ T,$

$P2 \equiv 0.171\ \delta g_L^b + 0.976\ \delta g_R^b + 0.109\ S - 0.081\ T,$

$P3 \equiv 0.00014\ S - 0.00094\ T + 0.757\ \delta g_L^\tau - 0.653\ \delta g_R^\tau,$

$P4 \equiv 0.00560\ S - 0.00399\ T + 0.653\ \delta g_L^\tau + 0.757\ \delta g_R^\tau,$

$P5 \equiv -0.01\ \delta g_L^b - 0.03\ \delta g_R^b + 0.768\ S + 0.639\ T,$

$P6 \equiv 0.02\ \delta g_L^b + 0.13\ \delta g_R^b - 0.631\ S + 0.765\ T.$

TABLE VI: Nonstandard Third Generation and Oblique Couplings

The parameters $\delta g_L^b, \delta g_R^b, S$ and T and the SM parameter $\alpha_s(M_Z)$ as determined by fitting to the observables of Table I. m_t is taken to be fixed at 179 GeV.

Parameter	LEP Only	Pull	LEP and SLC	Pull
δg_L^e	-0.000873 ± 0.000938	0.9	-0.00144 ± 0.000899	1.6
δg_R^e	-0.000574 ± 0.000768	0.7	-0.00119 ± 0.000712	1.7
δg_L^μ	-0.000787 ± 0.00207	0.4	-0.00035 ± 0.00206	0.2
δg_R^μ	-0.000518 ± 0.00226	0.2	0.0000348 ± 0.00224	0.0
P1	0.00105 ± 0.00119	0.9	0.00186 ± 0.00113	1.7
P2	-0.000928 ± 0.00301	0.3	-0.000266 ± 0.00299	0.1
P3	0.0000701 ± 0.000317	0.2	-0.0000102 ± 0.000315	0.0
P4	-0.0000132 ± 0.000517	0.0	-0.00028 ± 0.000507	0.6
$\alpha_s(M_z)$	0.130 ± 0.006		0.131 ± 0.006	
m_t	163 ± 15		162 ± 15	
$\chi^2_{\min}$/d.o.f.	11.4/8 (18% C.L.)		15.9/9 (7% C.L.)	

$P1 \equiv -0.766\delta g_L^e - 0.589\delta g_R^e - 0.18\delta g_L^\mu + 0.183\delta g_R^\mu$,

$P2 \equiv 0.0221\delta g_L^e - 0.00545\delta g_R^e + 0.673\delta g_L^\mu + 0.74\delta g_R^\mu$,

$P3 \equiv -0.642\delta g_L^e + 0.683\delta g_R^e + 0.27\delta g_L^\mu - 0.221\delta g_R^\mu$,

$P4 \equiv -0.0301\delta g_L^e + 0.431\delta g_R^e - 0.665\delta g_L^\mu + 0.609\delta g_R^\mu$.

TABLE VII: Nonstandard Lepton Couplings

The parameters $\delta g_L^e, \delta g_R^e, \delta g_L^\mu$ and δg_R^μ and the SM parameters $\alpha_s(M_Z)$ and m_t as determined by fitting to the observables of Table I.

Parameter	LEP Only	Pull	LEP and SLC	Pull
δg_L^e	0.00005 ± 0.00088	1.0	-0.00102 ± 0.00066	1.5
δg_R^e	0.00002 ± 0.00099	0.0	-0.00120 ± 0.00073	1.6
δg_L^μ	0.0000 ± 0.0021	0.0	0.0010 ± 0.0020	0.5
δg_R^μ	-0.0002 ± 0.0024	0.1	0.0010 ± 0.0023	0.4
δg_L^τ	-0.0001 ± 0.0010	0.1	0.0001 ± 0.0010	0.1
δg_R^τ	-0.0002 ± 0.0011	0.2	-0.0001 ± 0.0011	0.1
δg_L^b	-0.0048 ± 0.0066	0.7	0.0017 ± 0.0056	0.3
δg_R^b	0.000 ± 0.034	0.0	0.035 ± 0.028	1.2
δg_L^c	-0.008 ± 0.013	0.6	-0.012 ± 0.012	1.0
δg_R^c	0.013 ± 0.022	0.6	0.003 ± 0.021	0.2
δ_{UD}	0.0029 ± 0.0038	0.8	0.0029 ± 0.0038	0.8
P1	-0.004 ± 0.037	0.1	0.032 ± 0.031	1.0
P2	-0.009 ± 0.020	0.5	-0.015 ± 0.019	0.8
P3	0.012 ± 0.011	1.1	0.011 ± 0.011	1.0
P4	0.0001 ± 0.0029	0.0	0.0007 ± 0.0029	0.3
P5	-0.0014 ± 0.0020	2.1	-0.0041 ± 0.0020	2.1
P6	0.0002 ± 0.0014	0.1	-0.0001 ± 0.0014	0.1
P7	-0.00018 ± 0.00080	0.2	-0.00019 ± 0.00080	0.2
P8	-0.00002 ± 0.00072	0.0	-0.00076 ± 0.00063	1.2
P9	-0.00005 ± 0.00027	0.2	-0.00005 ± 0.00027	0.2
P10	0.00011 ± 0.00038	0.3	0.00011 ± 0.00038	0.3
P11	-0.00001 ± 0.00052	0.0	-0.00001 ± 0.00052	0.0
$\chi^2_{\min}$/d.o.f.	7.0/3 (7% C.L.)		10.4/4 (3% C.L.)	

$P1 \equiv 0.17\ \delta g_L^b + 0.91\ \delta g_R^b - 0.15\ \delta g_L^c - 0.34\ \delta g_R^c - 0.02\ \delta g_L^e - 0.02\ \delta g_R^e + 0.02\ \delta g_L^\mu + 0.02\ \delta g_R^\mu,$

$P2 \equiv -0.05\ \delta g_L^b - 0.37\ \delta g_R^b - 0.26\ \delta g_L^c - 0.89\ \delta g_R^c + 0.01\ \delta g_L^e + 0.01\ \delta g_R^e - 0.01\ \delta g_L^\mu - 0.01\ \delta g_R^\mu - 0.04\ \delta_{UD},$

$P3 \equiv -0.06\ \delta g_L^b - 0.04\ \delta g_R^b - 0.90\ \delta g_L^c + 0.27\ \delta g_R^c + 0.33\ \delta_{UD},$

$P4 \equiv 0.01\ \delta g_L^b + 0.03\ \delta g_R^b + 0.05\ \delta g_L^e + 0.05\ \delta g_R^e - 0.65\ \delta g_L^\mu - 0.75\ \delta g_R^\mu - 0.01\ \delta g_L^\tau - 0.02\ \delta g_R^\tau,$

$P5 \equiv 0.92\ \delta g_L^b - 0.17\ \delta g_R^b + 0.06\ \delta g_L^c - 0.02\ \delta g_R^c + 0.01\ \delta g_L^e + 0.01\ \delta g_L^\mu + 0.01\ \delta g_L^\tau - 0.01\ \delta g_R^\tau + 0.35\ \delta_{UD},$

$P6 \equiv 0.03\ \delta g_L^e + 0.03\ \delta g_R^e + 0.02\ \delta g_L^\mu + 0.02\ \delta g_R^\mu - 0.65\ \delta g_L^\tau - 0.76\ \delta g_R^\tau,$

$P7 \equiv -0.22\ \delta g_L^b + 0.04\ \delta g_R^b + 0.20\ \delta g_L^c - 0.09\ \delta g_R^c - 0.15\ \delta g_L^e + 0.16\ \delta g_R^e - 0.31\ \delta g_L^\mu + 0.27\ \delta g_R^\mu - 0.44\ \delta g_L^\tau + 0.38\ \delta g_R^\tau + 0.59\ \delta_{UD},$

$P8 \equiv 0.03 \; \delta g_R^b + 0.66 \; \delta g_L^e + 0.75 \; \delta g_R^e + 0.05 \; \delta g_L^\mu + 0.05 \; \delta g_R^\mu + 0.04 \; \delta g_L^\tau + 0.02 \; \delta g_R^\tau - 0.02 \; \delta_{UD}$,

$P9 \equiv 0.14 \; \delta g_L^b - 0.02 \; \delta g_R^b - 0.11 \; \delta g_L^c + 0.05 \; \delta g_R^c - 0.70 \; \delta g_L^e + 0.61 \; \delta g_R^e - 0.08 \; \delta g_L^\mu + 0.07 \; \delta g_R^\mu -$
$0.01 \; \delta g_L^\tau + 0.01 \; \delta g_R^\tau - 0.32 \; \delta_{UD}$,

$P10 \equiv -0.17 \; \delta g_L^b + 0.03 \; \delta g_R^b + 0.15 \; \delta g_L^c - 0.06 \; \delta g_R^c - 0.22 \; \delta g_L^e + 0.19 \; \delta g_R^e + 0.62 \; \delta g_L^\mu -$
$0.54 \; \delta g_R^\mu + 0.06 \; \delta g_L^\tau - 0.06 \; \delta g_R^\tau + 0.42 \; \delta_{UD}$,

$P11 \equiv 0.15 \; \delta g_L^b - 0.03 \; \delta g_R^b - 0.13 \; \delta g_L^c + 0.06 \; \delta g_R^c + 0.11 \; \delta g_L^e - 0.09 \; \delta g_R^e + 0.29 \; \delta g_L^\mu - 0.25 \; \delta g_R^\mu -$
$0.61 \; \delta g_L^\tau + 0.53 \; \delta g_R^\tau - 0.37 \; \delta_{UD}$.

TABLE VIII: Nonstandard $Z f \overline{f}$ Couplings

The parameters δg_L^f and δg_R^f as determined by fitting to the observables of Table I. m_t and $\alpha_s(M_Z)$ are taken to be fixed at 179 GeV and 0.125 respectively. The combination δ_{UD} is the combination of light-quark neutral-current couplings defined in the text.

6. Figure Captions

(1) A fit of the $Zb\bar{b}$ couplings $\delta g^g_{L,R}$ to the LEP data from the 1995 Winter Conferences. The SM parameters are chosen for this fit to be $\alpha_s(M_Z){=}0.112$, $m_t{=}177$ GeV and $m_H = 300$ GeV. The cross marks the central values obtainded in the fit and the three solid lines respectively denote the 1–, 2– and the 4–sigma error ellipsoids. The SM prediction lies at the origin, $(0,0)$, and so lies close to the 4–sigma ellipse. If the SLC value for A_{LR} is also included in the fit, then the error ellipses are translated so that the central value lies at the position of the circle.